Lifelines and earthquakes in the greater Seattle area,

by R.A. Haugerud, D.B. Ballantyne, C.S. Weaver, K.L. Meagher, and E.A. Barnett.

INTRODUCTION

The greater Seattle area, like any modern urban area, depends on highways, railroads, pipelines, ports, airports, communications, and the electrical power system to sustain its economic life. When any of these lifeline systems are disrupted, economic losses can occur. Seattle and Puget Sound are earthquake country. Maintenance of a healthy economy requires planning for the effects of future large earthquakes.

Imagine a major winter windstorm. The primary disruption is to the electrical system. Falling trees break powerlines and that often causes failures at smaller distribution substations, resulting in widespread outages. Often hundreds of thousands of residents and businesses are without power for a day or more. The effects of windstorms on lifeline systems are fairly easy to visualize.

Earthquakes present a more complex challenge. First, lifelines are dependent on many components operating together to make the system functional. Failure of one critical component can bring down the entire system. Second, earthquakes tend to effect many lifeline systems at once. Failures in the highway system may make restoration of a critical electrical power substation or sewer treatment plant more difficult. Third, earthquakes can cause significant failure of structures such as bridges that are not quickly or easily replaced. And fourth, as failure may occur on several systems, it may be difficult to immediately determine priorities and strategies for recovery.

This map shows the relation of selected lifeline elements to selected earthquake hazards. The shaded-relief base allows quick, qualitative recognition of steep slopes and river valleys. Superimposed on this base are selected lifeline system elements: major electric power transmission lines and substations, water supply pipelines, major sewer pipelines and treatment plants, liquid fuel pipelines, natural gas pipelines, and major ports and airports. Also shown are three elements of the regional earthquake hazard: 1) Unconsolidated young deposits that have a high liquefaction potential and are likely to amplify seismic shaking. 2) An east-west zone that follows the Seattle fault, within which it is conceivable that a crustal earthquake may rupture to the surface. 3) The limit of buried, low-seismic wave-velocity sedimentary rocks within the Seattle basin. Reverberation of seismic waves within this basin may prolong seismic shaking in the overlying area.

The map is designed to give citizens, engineers, planners, and decision-makers an overview of lifelines and earthquake hazards in the greater Seattle area. The map does not provide information for engineering purposes, nor does it provide useful site-specific information. The map also shows that much of the region's infrastructure is concentrated in the Seattle fault zone, and thus understanding the behavior of the Seattle fault is critical to ensuring that the area's lifelines function as expected after the next major earthquake.

LIFELINE SYSTEMS

Water

The three largest water suppliers in the region are the cities of Everett, Seattle, and Tacoma. In all three cases, the primary supply comes from surface water gathered on the western slopes of the Cascade Mountains. Seattle and Tacoma also have supplementary groundwater supplies. The three suppliers' systems are substantially independent of one another, with only small interties. An intertie is planned between the Seattle and Tacoma systems. These three suppliers provide both retail and wholesale service. Smaller water purveyors depend on supplies from Everett, Seattle, and Tacoma, and (or) their own groundwater (and to a limited degree surface water) supplies.

The map shows source rivers and reservoirs where the surface water enters the transmission systems, and follows the transmission systems to their terminal reservoirs. The transmission systems generally run east to west and in all cases cross valleys with unconsolidated young alluvial deposits.

Wastewater

The largest wastewater system in the region is operated by King County, and serves most of the county's urban area. Gravity interceptors collect sewage and deliver it to large treatment plants in Renton and at West Point, in many places traversing liquefiable soils en route. The Renton plant, at the southern end of Lake Washington, serves the region east of Lake Washington and the Kent Valley. Its outfall parallels the Duwamish River and discharges into Puget Sound. The West Point plant, northwest of Elliott Bay, serves the area west of Lake Washington and discharges via a short outfall into Puget Sound.

The cities of Everett and Tacoma operate wastewater collection and treatment facilities. The Everett treatment plant is across the Snohomish River from the city. The Tacoma treatment plant is on former tide flats adjacent to the Puyallup River.

Electrical Power

The major electric power producer in the Pacific Northwest is the Bonneville Power Administration, which has hydroelectric plants along the Columbia and Snake rivers far to the east. BPA sells power to the major distributors in the region, including Puget Sound Energy, Seattle City Light, Snohomish County PUD, and Tacoma Public Utilities. Each of these distributors has some generation capacity. Much of the BPA power moves through the 500 and 345 kV substations shown on the map. A 230 kV grid also provides a significant level of redundancy.

Natural Gas

Natural gas is transported into the region from Canada, through a pair of high-pressure transmission lines (26-inch constructed in 1952, and 30-inch constructed in 1970) located in a common corridor. Williams Natural Gas Pipeline Company owns both lines. In the event of a failure, gas can be supplied from the south. These pipelines cross the east-west trending river valleys, which run from the Cascades to Puget Sound. Natural gas is distributed in the region primarily by Puget Sound Energy (PSE). PSE has connections to the Williams pipelines distributed along their length.

Liquid Fuel

Olympic Pipeline Company transports liquid fuel in a pair of pipelines (16-inch and 20-inch) from refineries at Ferndale, Cherry Point, and Anacortes (all north of the map) south to Renton. One line continues on to Portland. The pipelines carry about 14 million gallons per day. Lateral pipelines transport fuel to the Ports of Seattle and Tacoma, Seattle-Tacoma Airport, and distribution points from where it is

trucked to gas stations. About 75% of the gasoline used in the region is delivered through these pipelines. Approximately 700 tank trucks per day would be required to move the fuel the pipeline transports south to Portland.

Highways

Primary regional vehicle movement is north-south. I-5 carries between 150,000 and 300,000 vehicles per day, depending on the location. I-405 carries about 200,000 vehicles in Bellevue. The east-west I-90 bridge carries nearly 150,000 vehicles per day while the SR-520 bridge moves approximately 125,000. Most of the I-5 bridges were constructed between the mid-1950s and the mid-1970s.

Railroads

Both Burlington Northern-Santa Fe and Union Pacific railroads serve the region. More than 50 freight trains per day move through the Kent Valley south of Seattle, with more than 30 passenger trains per day expected once the heavy-rail component of Sound Transit is implemented in the next few years. Railroad bridges over the Duwamish, and Puyallup rivers were built before 1910. The railroad alignment between Seattle and Tacoma lies on liquefiable unconsolidated young deposits in the Kent and Puyallup River valleys. North of Seattle, the main Burlington Northern-Santa Fe route runs along the Puget Sound, where it is frequently impacted by landslides, particularly during the winter rainy season.

Airports

Seattle Tacoma International Airport, between Seattle and Tacoma, is the area's primary commercial airport, with approximately 25 million passengers and 200,000 landings annually. Boeing Field, along I-5 in south Seattle, services a significant air freight business. Boeing's 747 - 777 assembly plant is located at Paine Field south of Everett. McChord Air Force Base, south of Tacoma, supports large transport planes. All of these airports are on competent soils with the exception of Boeing Field, which is in the liquefiable Duwamish River valley.

Marine Facilities

The ports of Seattle and Tacoma are leaders in international trade, with each port shipping approximately 1 million twenty-foot equivalent units (TEUs) per year. About 60 percent of imports move through to inland domestic markets. The Port of Everett has some log-export traffic and is home to part of the U.S. Navy's Pacific fleet.

Most Port of Seattle marine facilities are located at the former estuary of the Duwamish River on Elliott Bay. The Port of Tacoma is located on the delta of the Puyallup River on Commencement Bay. Both locations are highly liquefiable.

EARTHQUAKE HAZARDS

Older residents can remember that in 1949 and 1965, earthquakes of magnitude 7.1 and 6.5, respectively, hit the Puget Sound region. Eight people were killed in each earthquake. Damage from smaller recent earthquakes, such as the 1996 Duvall earthquake that disrupted a Mariners' baseball game, has been very slight.

Despite the lack of recent, large, damaging earthquakes, earth scientists and engineers now understand that earthquake hazards in the Seattle area are greater than previously known. In the early 1990s scientists and engineers accepted geologic evidence that great subduction zone earthquakes, of magnitude 8 to 9, repeatedly strike along the Washington coast. In 1992, geologists recognized that raised and lowered beaches on Bainbridge Island recorded a large earthquake on the Seattle fault about 1100 years ago. Since then, geologic and geophysical field investigations at an accelerating pace have sought to understand the potential for large-magnitude shallow earthquakes in the Seattle area.

The results have been sobering. Changes in the elevation of beaches, particularly in southern Puget Sound, suggest one or more large events in addition to the Seattle fault event about 1100 years ago. Geologic study of trenches across the Seattle fault on Bainbridge Island has found evidence of as much as a meter of slip during an earthquake within the last 4500 years. Preliminary geophysical measurements show crustal contraction across the Seattle fault, clear evidence that strain is slowly building toward the next earthquake.

Geologic Setting

Western Washington lies in the contact between two of the Earth's large crustal plates. The Juan de Fuca plate, which forms the floor of the northeastern Pacific Ocean, moves northeastward with respect to the North American plate at an average rate of about 4 centimeters (1.5 inches) per year, as indicated by the arrow in Figure 1. As it collides with North America, the Juan de Fuca plate slides (or subducts) beneath the continent and sinks slowly into the earth's mantle (the 3,000-kilometer-thick rocky shell between the outermost crust and the molten outer core of the earth). The shallow, east-dipping zone of contact between the plates is the Cascadia fault. The collision of these plates produces the Cascade volcanoes and earthquakes in three source zones.

Subduction Zone

The area just offshore, where the Cascadia fault is near the surface of the Earth, is called the Cascadia subduction zone. Now, as at most times, there is little slip on the Cascadia fault in the subduction zone. Eastward motion of the Juan de Fuca plate is absorbed by compression of the North American plate. Records provided by buried soil layers, dead trees, and deep-sea deposits indicate to geologists that the Cascadia fault ruptures and releases this compression in large—magnitude 8 to 9—earthquakes about every 500-600 years. It is the upper portion of the shallowly dipping Cascadia fault that ruptures during these events; most of the rupture area is offshore. The last such earthquake occurred on January 26, 1700.

When the Cascadia fault ruptures, it will likely cause: 1) Severe ground motions along the coast, with shaking in excess of 1 g in many locations (1 g is equal to the acceleration of gravity, 0.5 g is half the acceleration of gravity). The greater Seattle area will see 0.2 to 0.3 g accelerations from a subduction-zone earthquake. 2) Because of the very large fault area involved, slip will produce strong motions that may last for two to four minutes as the earthquake propagates along the fault, and include seismic waves of very long period (20 seconds or more). These long-period waves may particularly effect very tall structures, and long structures such as bridges. 3) Tsunamis generated by sudden uplift of the sea floor above the fault. Effects of past tsunamis are among the evidence observed by geologists to infer the history of earthquakes in the subduction zone. 4) Effects in all of Cascadia's major population centers, from Vancouver, B.C., to Portland, putting strong stresses on the regional infrastructure.

Benioff (Deep) Zone

As the Juan de Fuca plate subducts beneath North America, it becomes denser than the surrounding mantle rocks and breaks apart under its own weight, causing Benioff zone earthquakes. Beneath Puget Sound the Juan de Fuca plate reaches a depth of 40-60 km and begins to bend even more steeply downward, forming a "knee" (Figure 1). It is at this knee where the largest Benioff zone earthquakes occur: both the 1949 event near Olympia (southwest of Tacoma) and the 1965 event near the Seattle-Tacoma International Airport occurred at the knee. But we expect that Benioff zone earthquakes as large as magnitude 7.5 are expected everywhere west of the eastern shores of Puget Sound.

Like subduction earthquakes, Benioff zone earthquakes have several distinctive characteristics. First, because they occur at depths of 40 kilometers or more, high frequency energy has been attenuated. On hard rock, peak ground accelerations are no more than about 0.2 to 0.3 g. Second, they tend to be felt over much broader areas than a shallow earthquakes of comparable magnitude. And third, significant aftershocks aren't expected, an important point for post-earthquake response.

Crustal Zone

The third source zone is the crust of the North American plate. Of the three source zones, this is the least understood. A variety of lines of evidence lead to the conclusion that the Puget Lowland area is currently shortening north-south at a rate of about 1/2 cm (one-fifth of an inch) per year. Where, and how, this shortening is occurring is not well understood, but at least some of it is occurring on the Seattle fault.

The structure of the crust in the Puget Sound area is complex, with large sedimentary rock-filled basins beneath Tacoma, Seattle and Everett. The Seattle basin is the deepest, at 8-10 km. Its approximate extent is shown on the map. The Seattle fault forms the south margin of the Seattle basin; the lack of coincidence on the map between the fault zone and the buried basin margin reflects the south dip of the Seattle fault—at depth, the fault is farther south.

Other active faults may be present in the greater Seattle area (Figure 2), but geologists have only documented young (in the last 14,000 years) motion on the Seattle fault. How many other crustal faults pose significant earthquake hazards to the Puget Sound region is not yet known, but geologists and geophysicists are studying the South Whidbey Island fault, the Olympia fault (southwest of the map), and the Devils Mountain fault (north of the map) for evidence of young earthquakes.

As noted above, the seismic potential of the Seattle fault has been only recently appreciated. Because crustal earthquakes are shallow—at depths of 5 to 20 km—and may occur directly beneath urban areas, they have the potential to do great damage. The 1995 Kobe (Japan) and 1994 Northridge (California) earthquakes, with ground motions of 0.5 to 1.0 g, may be good analogs for a crustal earthquake in the greater Seattle area.

Probabilistic Ground Motion Map

The probabilistic hazard map (Figure 3) shows the expected peak horizontal ground motions on a hard rock site with a 2% probability of exceedance in 50 years, aggregated from all three sources. Note that along the coast the contour lines strike more or less south-north—in this region the hazard is dominated by the subduction zone source, and farther east shaking is likely to be less. Moving into Puget Sound, contours swing east-west—the effect of the Benioff zone, which appears to produce more earthquakes beneath Puget Sound than farther south or north. The bullseye over central Puget Sound reflects our new understanding of the Seattle fault. If geologic studies now in progress sustain our current view of Seattle fault zone hazards, it is likely that the greater Seattle area will see upward revisions in building codes.

Attenuation and Amplification

The type and depth of near-surface deposits (down to about 30 meters) can greatly affect the intensity of earthquake shaking at a given site. Poorly consolidated, water-saturated soils (seismologists and engineers call the entire top 30 meters of such deposits soils) usually amplify incoming seismic motions, sometimes by as much as a factor of two. Typically, such poorly-consolidated soils are found in river and stream valleys. Areas of artificial fill are also often poorly consolidated.

Earthquake shaking may be prolonged above the Seattle basin. Modeling studies suggest that large buried lenses of sedimentary rocks with low seismic-wave velocities can act as reverberation chambers, trapping seismic waves and producing echoes.

Earthquake Effects

When an earthquake occurs, there are a number of possible effects. Here we limit our discussion to some of the most important with respect to the lifelines shown on the map: surface rupture, ground shaking, liquefaction, and earthquake-induced landslides.

Surface rupture is a new concern in the Puget Sound region. Until the discovery of the changes in elevations of beaches on Bainbridge Island, it was unclear whether recent surface faulting had occurred in the area. With the documentation of surface rupture on Bainbridge Island in the last 14,000 years and detailed geophysical surveys along the Seattle fault, it now seems likely that there is a broad zone (striped pattern on the map) where surface rupture may occur. Although for any given earthquake the changes of surface rupture may be small, it may be desirable for lifeline system engineers to at least consider such a possibility. Several lifeline systems cut north-south through this zone of possible surface faulting.

Ground shaking occurs in a wide area following an earthquake. Because of the complexity of three source zones, it is useful to use the probabilistic hazard map (Figure 3) as an initial guide to areas of strong shaking. However, engineers know from experience that unconsolidated young deposits often amplify ground motion, sometimes by a factor of two or more. Areas of unconsolidated deposits shown on the map should be viewed with caution—ground motions in these areas will likely be more intense than predicted for hard rock sites. Significant sections of major sewer and petroleum pipelines south of Seattle cross such areas. In addition to unconsolidated-soil amplification, areas over the Seattle basin may experience prolonged ground shaking from the deep sedimentary basin effect. Earth scientists are actively working to quantify these effects in the greater Seattle area.

Liquefaction is another problem in areas of unconsolidated young deposits. Strong shaking may cause water stored within the soil to be suddenly released. When this happens, the soil loses its shear strength and its ability to support large loads. Structures may fail. If adjacent to a riverbank, or on a slope, ground can move laterally (lateral spread), carrying with it buried pipelines and foundations. Generally, many of the same areas subject to amplified ground shaking are also susceptible to liquefaction; thus the shaded areas on our map carry double hazard significance. Liquefaction susceptibility depends on the details of soil composition and structure. It can be (and in some cases has been) mapped in more detail than is shown here.

Finally, steep slopes may produce landslides during earthquakes. Some landslides do not occur in the first few minutes following an earthquake, but days later. There were numerous landslides during and after the 1949 and 1965 earthquakes; some closed roads and swept sections of railroad track into Puget Sound. Steep slopes throughout the greater Seattle area are candidates for earthquake-induced failure, though we have not attempted to delineate these areas.

LIFELINE VULNERABILITY TO EARTHQUAKES

The vulnerability of a lifeline to earthquakes is related to the type of structure and to the specific earthquake hazard. Lifeline building structures are vulnerable to earthquake shaking, just as is any building structure. There are many special types of structures found in lifeline systems that have failure modes not commonly found elsewhere.

Pipelines - Water, Wastewater, Liquid Fuel, and Natural Gas

Buried pipelines carrying water, wastewater, natural gas, and liquid fuel are vulnerable to surface faulting, shaking (wave propagation), liquefaction/lateral spread, and landslides. Pipelines constructed of brittle materials are the most vulnerable. Water and older gas distribution (low pressure) systems often

have significant amounts of brittle cast iron. Asbestos cement found in many water systems is also brittle. Pipelines constructed of ductile materials such as steel and ductile iron are more resistant to earthquake ground motion. If liquefaction occurs, joint restraint is also important. Welded joints used on gas and liquid fuel lines, and "restrained" joints used for some water pipelines are preferred in areas subject to liquefaction. Pipelines buried in liquefiable soils can have failure rates an order of magnitude larger than those in stable soils.

Natural gas and liquid fuel pipelines constructed of steel with welded joints have performed well except in the most extreme conditions. Pipeline joints welded with older techniques are in some cases more brittle, and have failed.

In an earthquake, it is common for many water pipelines to fail, which results in quickly draining the water system. Water is then not available for fire suppression. This scenario occurred following the 1995 Kobe (Japan), 1994 Northridge (California), 1989 Loma Prieta (California), 1923 Tokyo (Japan) and 1906 San Francisco (California) earthquakes. In the worst earthquakes, such as Kobe, the water service was not fully restored for two months.

Sewer pipelines used to collect sewage are vulnerable to flotation if the ground around them liquefies. As these are often "gravity" systems, a change in grade can impact system operation. In the 1965 Seattle earthquake, a 108-inch diameter sewer just east of Metro's Renton wastewater treatment plant floated upward approximately two feet. Many sewers floated in the 1989 Loma Prieta earthquake, particularly in Santa Cruz, and in the 1995 Kobe Earthquake.

Tanks and Reservoirs

Liquids, such as water and liquid fuels, slosh in tanks and reservoirs. This movement, comprising impulsive and convective components, can load the tank walls beyond their capacity. Initially, an unanchored tank may rock, breaking connecting piping. As sloshing continues, rocking may cause the tank to buckle or burst. Sloshing can also damage tank roofs and immersed components such as baffles and sludge rakes. Tanks containing liquid fuel have been damaged, and their contents burned. Earthen reservoirs and dams are vulnerable, particularly to liquefaction. The Lower Van Norman Dam nearly failed in the 1971 San Fernando (California) earthquake.

Electrical Power Facilities

Regional power systems failed following the 1995 Kobe, 1994 Northridge, and 1989 Loma Prieta earthquakes. Such failures are often due to self-protecting features built into the system, and can often be restored within 24 to 72 hours. The most vulnerable components of electrical power systems are porcelain insulators. The higher the voltage, the larger—and more vulnerable—the insulator. As a result, high voltage substations, particularly 230 kV and above, are vulnerable to earthquake ground motion. Transformer bushings are one type of insulator. Live tank circuit breakers, a commonly used type in the industry, have not performed well in earthquakes. Rigid busses connecting substation equipment transfer dynamic loads from other equipment, and exacerbate insulator failures. If well anchored, lower voltage equipment functions well.

Power poles have performed well, except when they are founded on unstable soils where landslides or liquefaction can occur. In the 1993 Landers (California) earthquake, a fault ruptured through the base of a four-legged transmission tower. The tower was distorted, but it did not collapse. Low voltage power lines can slap against one another causing a circuit to short. Higher voltage lines have greater separation, and thus are less prone to this type of failure.

Highways

Bridges are the most vulnerable component of highway systems. More robust bridge designs were developed in the 1970s and 1980s. Older bridges may be more prone to failure. Bridge decks can slide off their seats if they are too narrow or not adequately restrained. Supporting columns can buckle if they are overloaded and not designed with adequate ductility. Single span bridges supported on abutments perform better. Bridge foundations in liquefiable soils can move, allowing the spans they support to slide off.

Railways

Railway bridges have in general performed well, probably as a result of the very large loads they are designed to carry. Earthquakes in the U.S. and Japan have not tested the resistance of railroad bridges to liquefaction.

Airports

Airport runways may be vulnerable to liquefaction. In the 1989 Loma Prieta Earthquake, 3000 feet at the end of the main runway of the Oakland Airport were taken out of service when liquefied sand spurted up through runway joints. Airport control tower glass is vulnerable, as many tower cabs are not adequately designed to transfer the roof load to the structure. Roof movement can cause the glass to rack, and break. Airports are highly dependent on power to maintain radar, communication, and lighting systems. Both commercial and backup power have not been reliable in earthquakes.

Marine Facilities

Piers are vulnerable to liquefaction, which can result in pile failure and loss of load carrying capacity, and possible failure of supported structures. Further, sea wall foundations can liquefy, as occurred in Kobe, resulting in lateral movement towards the water. Such movement shut down nearly all of the Port of Kobe's 200 berths following the 1995 earthquake.

ABOUT THE MAP

The base map was derived from standard USGS 10-meter digital elevation models (DEMs), supplemented with LIDAR data (courtesy of Kitsap County) for Bainbridge Island. Shorelines and streams are from USGS digital line graphs (DLGs) derived from standard 1:100,000-scale maps (see *http://edcwww.cr.usgs. gov/dsprod/prod.html*)

The extent of unconsolidated young (Holocene) deposits is simplified from an unpublished digital geologic compilation by Haugerud. Primary sources for this compilation are USGS 1:100,000-scale mapping in the Cascade foothills (R.W. Tabor, USGS, personal communication), Washington Division of Geology and Earth Resources 1:100,000-scale compilation maps (J. Eric Schuster, WDGER, personal communication), and an unpublished compilation map of King County (Derek Booth, King County, personal communication). The extent of possible rupture along the Seattle fault zone was estimated by Haugerud from the extent of past faulting and topography. The limit of buried young sedimentary rocks of the Seattle basin was interpreted by Richard Blakely (USGS, personal communication) from geophysical surveys.

We thank Ken Conradi (City of Seattle) Michael Jenkins (King County), Louis Kempner and Bob White (Bonneville Power Administration), Kurt Myking (City of Tacoma), and Kathy Reed (Olympic Pipeline Company), for assistance with digital and paper map data on the locations of lifelines. Rail lines and natural gas pipelines are from USGS DLG data.

This report is a joint effort by the U.S. Geological Survey and EQE International. Work by USGS staff was funded by the Earthquake Hazard Program, Urban Hydrologic and Geologic Hazard Initiative, and National Cooperative Geologic Mapping Program.

Seattle Metropolitan Area Lifelines Map

8.5 X 11 Image

The following page is a simplified version of a 24" x 35" map presented in OFR 99-387.

Orange-brown areas are underlain by unconsolidated young deposits that are likely to have moderate to high liquefaction susceptibility, and to amplify ground shaking during earthquakes.

The orange cross-ruled area across the middle of the map is a zone along the Seattle fault within which recent work suggests there is some chance of ground rupture during a large earthquake on the Seattle fault.